CP violation in polarized $b \to dl^+l^-$: A Detailed Standard Model Analysis

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The electroweak CP violating rate asymmetries in the decay $b \to dl^+l^-$ are reexamined in detail and updated. In particular, the rate asymmetries are studied when one of the final state leptons is polarised. We find an estimate for the asymmetry of $(5 \div 15)\%$ in the polarised decay spectrum which is close to known results for the unpolarised case. Interestingly, in the region separating the $\rho - \omega$ and $c\bar{c}$ resonances, which is also theoretically cleanest, the polarised contribution to the asymmetry is larger than the unpolarised result. A 3σ signal for direct CP violation, requires about 10^{10} $B\bar{B}$ pairs at a B factory. In general these results indicate an asymmetric contribution from the individual polarisation states to the unpolarised CP asymmetry; an atribute for any new physics searches.

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I. INTRODUCTION

In the standard model (SM), the rare decays which involve flavor changing neutral current decays are important probes for new physics [1]. In general, due to the well known GIM mechanism [2] these processes are strongly suppressed along with the usual CKM suppression. All these features therefore point to potential sources or act as rich test ground for any new physics, such that any deviation from the SM expectations is an unambiguous signature for new physics. One of the key observables involving FCNC is the radiative B decay, $B \to X_s\gamma$. Measurements of the branching ratio for this decay [3] are in very good agreement with the SM calculations [4, 5] at the current level of accuracy imposing strong constraints on new physics scenarios.

The parton level rare semi-leptonic decays, $b \to ql^+l^-$ ($q = d, s$), can provide alternative sources to discover new physics where in particular the lepton pair gives easy access to decay spectra in dependence of the invariant mass of the lepton pair providing detailed dynamical information. Moreover, appropriate experimental cuts allow to separate out theoretically clean regions of the phase space. The semi-leptonic decays are described by QCD corrected effective Hamiltonians which are expanded in a set of effective operators multiplied by so called Wilson coefficients acting as couplings and being perturbatively calculable. In new physics scenarios the Wilson couplings can get modified and, in addition,

new operator structures can arise. In such decays, the standard observables like the decay rate, lepton polarization asymmetries and the forward-backward asymmetry depend on different quadratic combinations of the Wilson coefficients and can be studied kinematically as a function of the invariant di-lepton mass. Therefore, detailed measurements of these observables provide extensive tests of the effective Hamiltonian and hence of the SM and new physics scenarios. Before the B factories such as BaBar and Belle the best experimental limits for the inclusive branching ratios $BR(b \to sl^+l^-)$ with $l = e, \mu$ as measured by CLEO [6] have been an order higher than the SM estimates [7]. However, the first measurement of this decay has been reported by Belle [8] and is in agreement with the SM expectations and hence further constrains any extensions to the SM.

In addition to the above observables it is possible to construct CP violating rate asymmetries which are sensitive to further different combinations of Wilson couplings. Needless to say, that apart from new physics searches, CP violating effects in rare b-decays are also interesting in its own right. In these proceedings we summarize the main results of our recent analysis of CP violating effects in the decay $b \to dl^+l^-$ within the SM, including the case when one of the leptons is polarized [9].

Standard model CP violation in the decays $b \to ql^+l^-$ has been studied previously in Refs. [10, 11] for unpolarized leptons. Very recently, a study of CP violation in the polarized decay $b \to dl^+l^-$ has also been performed in a model independent framework [12].

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II. THEORETICAL RATE ESTIMATES

The parton level process with the QCD corrected effective Hamiltonian describing the decay $b \to d l^+ l^-$ can be described by the matrix element [10, 13]

$$
M = K \Big[C_9^{\text{eff}}(\bar{d}\gamma_\mu P_L b)\bar{l}\gamma^\mu l + C_{10}(\bar{d}\gamma_\mu P_L b)\bar{l}\gamma^\mu\gamma^5 l \\
- 2C_7^{\text{eff}}\bar{d}i\sigma_{\mu\nu}\frac{q^\nu}{q^2}(m_b P_R + m_d P_L)b\bar{l}\gamma^\mu l \Big], \quad (1)
$$

with $K := \frac{G_F \alpha V_{tb}V_{td}^*}{\sqrt{2}\pi}$. In Eq. (1) the notations employed are the standard ones and q denotes the four momentum of the lepton pair.

In the SM, except for C_9^{eff}, the Wilson couplings are real and analytic expressions can be found in the literature [13, 14, 15]. In our analysis [9] we use

$$
C_7^{\text{eff}} = -0.310 , \quad C_{10} = -4.181 . \quad (2)
$$

The effective coefficient C_9^{eff} can be parametrized in the following way [10]:

$$
C_9^{\text{eff}} = \xi_1 + \lambda_u \xi_2 , \quad \lambda_u = \frac{V_{ub}V_{ud}^*}{V_{tb}V_{td}^*} , \quad (3)
$$

with

$$
\xi_1 \simeq 4.128 + 0.138\,\omega(\hat{s}) + 0.36\,g(\hat{m}_c, \hat{s}), \quad (4)
$$
$$
\xi_2 \simeq 0.36\,[g(\hat{m}_c, \hat{s}) - g(\hat{m}_u, \hat{s})] . \quad (5)
$$

Here, $\hat{s} = q^2/m_b^2$ and $\hat{m}_q = m_q/m_b$ are dimensionless variables scaled with respect to the bottom quark mass. The function $\omega(\hat{s})$ represents one loop corrections to the operator O_9 [16] and the function $g(\hat{m}_q, \hat{s})$ represents the corrections to the four-quark operators $O_1 - O_6$ [15].

In addition to the short distance contributions described above, the decays $B \to X_d l^+ l^-$ also receive long distance contributions from the tree-level diagrams involving $u\bar{u}$, $d\bar{d}$, and $c\bar{c}$ bound states, $B \to X_d(\rho, \omega, J/\psi, \psi', ...) \to X_d l^+ l^-$. In our analysis the ρ, ω, and $c\bar{c}$ resonances have been taken into account by an appropriate modification of the functions $g(\hat{m}_q, \hat{s})$.

A. Differential decay spectrum: Unpolarized case

Neglecting any low energy QCD corrections ($\sim 1/m_b^2$) [7, 17] and setting the down quark mass to zero, the unpolarized differential decay width as a function of the invariant mass of the lepton pair is given by

$$
\frac{d\Gamma}{d\hat{s}} = \frac{G_F^2 m_b^5 \alpha^2}{768\pi^5}|V_{tb}V_{td}^*|^2(1-\hat{s})\sqrt{1-\frac{4\hat{m}_l^2}{\hat{s}}}\Delta(\hat{s}), \quad (6)
$$

with the kinematic factors

$$
\Delta(\hat{s}) = \Big[12\text{Re}(C_7^{\text{eff}}C_9^{\text{eff}*})F_1(\hat{s}) + \frac{4}{\hat{s}}|C_7^{\text{eff}}|^2 F_2(\hat{s})\Big] \\
\times(1+\frac{2\hat{m}_l^2}{\hat{s}}) + (|C_9^{\text{eff}}|^2 + |C_{10}|^2)F_3(\hat{s}) \\
+ 6\hat{m}_l^2(|C_9^{\text{eff}}|^2 - |C_{10}|^2)F_1(\hat{s}) ,
$$
$$
F_1(\hat{s}) = 1 - \hat{s} ,
$$
$$
F_2(\hat{s}) = 2 - \hat{s} - \hat{s}^2 ,
$$
$$
F_3(\hat{s}) = 1 + \hat{s} - 2\hat{s}^2 + (1-\hat{s})^2\frac{2\hat{m}_l^2}{\hat{s}} . \quad (7)
$$

In Eq.(7) the hat denotes all parameters scaled with respect to the b quark mass m_b. Note that the physical range for $\hat{s}$ is given by $4\hat{m}_l^2 \leq \hat{s} \leq 1$.

As usual we remove uncertainties in Eq. (6) due to the bottom quark mass (a factor of m_b^5) by introducing the charged current semi-leptonic decay rate

$$
\Gamma(B \to X_c e\bar{\nu}_e) = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 f(\hat{m}_c)\kappa(\hat{m}_c) \quad (8)
$$

where $f(\hat{m}_c)$ and $\kappa(\hat{m}_c)$ represent the phase space and the one-loop QCD corrections to the semi-leptonic decay and can be found in [10]. Therefore the differential branching ratio can be written as

$$
\frac{d\,\text{BR}}{d\hat{s}} = \frac{\alpha^2}{4\pi^2}\frac{|V_{tb}V_{td}^*|^2}{|V_{cb}|^2}\frac{\text{BR}(B \to X_c e\bar{\nu}_e)}{f(\hat{m}_c)\kappa(\hat{m}_c)}(1-\hat{s})\,a\,\Delta(\hat{s}), (9)
$$

with the threshold factor $a \equiv \sqrt{1-\frac{4\hat{m}_l^2}{\hat{s}}}$.

B. Differential decay spectrum: Polarized case

The potential richness of measuring the lepton polarisation was first realised by Hewett [18] and Krüger and Sehgal [19]. These authors showed that additional independent information can be obtained on the quadratic functions of the effective Wilson couplings, C_7^{eff}, C_{10} and C_9^{eff}. Defining a reference frame with three orthogonal unit vectors $\mathbf{e}_L$, $\mathbf{e}_N$ and $\mathbf{e}_T$, such that

$$
\mathbf{e}_L = \frac{\mathbf{p}_{l^-}}{|\mathbf{p}_{l^-}|} ,
$$
$$
\mathbf{e}_N = \frac{\mathbf{p}_q \times \mathbf{p}_{l^-}}{|\mathbf{p}_q \times \mathbf{p}_{l^-}|} , \quad (10)
$$
$$
\mathbf{e}_T = \mathbf{e}_N \times \mathbf{e}_L ,
$$

where $\mathbf{p}_q$ and $\mathbf{p}_{l^-}$ are the three momentum vectors of the quark and the l^- lepton, respectively, in the $l^+ l^-$ center-of-mass system. For a given lepton l^- spin direction $\mathbf{n}$, which is a unit vector in the l^- rest frame, the differential decay spectrum is of the form [19]

$$
\frac{d\Gamma(\hat{s}, \mathbf{n})}{d\hat{s}} = \frac{1}{2}\left(\frac{d\Gamma(\hat{s})}{d\hat{s}}\right)_0\Big[1 + (P_L\mathbf{e}_L + P_T\mathbf{e}_T + P_N\mathbf{e}_N)\cdot\mathbf{n}\Big],
$$
$$
(11)
$$

where the unpolarized decay rate $\left(\frac{d\Gamma(\hat{s})}{d\hat{s}}\right)_0$ can be found in Eq. (6) and the polarisation components P_i $(i = L, N, T)$ are obtained from the relation

$$P_i(\hat{s}) = \frac{d\Gamma(\mathbf{n} = \mathbf{e}_i)/d\hat{s} - d\Gamma(\mathbf{n} = -\mathbf{e}_i)/d\hat{s}}{d\Gamma(\mathbf{n} = \mathbf{e}_i)/d\hat{s} + d\Gamma(\mathbf{n} = -\mathbf{e}_i)/d\hat{s}} \ . \quad (12)$$

The resulting polarisation asymmetries are

$$
\begin{aligned}
P_L(\hat{s}) &= \frac{a}{\Delta(\hat{s})}\Big[12\mathrm{Re}(C_7^{\mathrm{eff}}C_{10}^*)(1-\hat{s}) \\
&\quad +2\mathrm{Re}(C_9^{\mathrm{eff}}C_{10}^*)(1+\hat{s}-2\hat{s}^2)\Big], \\
P_T(\hat{s}) &= \frac{3\pi\hat{m}_l}{2\Delta(\hat{s})\sqrt{\hat{s}}}(1-\hat{s})\Big[2\mathrm{Re}(C_7^{\mathrm{eff}}C_{10}^*) \\
&\quad -4\mathrm{Re}(C_7^{\mathrm{eff}}C_9^{\mathrm{eff}\,*})-\frac{4}{\hat{s}}|C_7^{\mathrm{eff}}|^2 \\
&\quad +\mathrm{Re}(C_9^{\mathrm{eff}}C_{10}^*)-|C_9^{\mathrm{eff}}|^2\hat{s}\Big], \\
P_N(\hat{s}) &= \frac{3\pi\hat{m}_l a}{2\Delta(\hat{s})}(1-\hat{s})\sqrt{\hat{s}}\,\mathrm{Im}(C_9^{\mathrm{eff}\,*}C_{10}) \ , \quad (13)
\end{aligned}
$$

where we differ by a factor of 2 in P_T with respect to the results obtained in [19]. The above expressions for P_i agree with [20] for the SM case. Clearly, the polarisation asymmetries in Eq. (13) have different quadratic combinations of the Wilson couplings and any alteration in the values of these couplings can lead to changes in the asymmetries. Hence, these are sensitive to new physics and can also probe the relative signs of the couplings C_7^{eff}, C_9^{eff} and C_{10}. The normal polarisation asymmetry P_N is proportional to $\mathrm{Im}(C_9^{\mathrm{eff}}C_{10}^*)$ and is thus sensitive to the absorptive part of the loop contributed by the charm quark. Note also that the transverse and normal asymmetries P_T and P_N, respectively, are proportional to $\hat{m}_l$ and thus the effects can be significant only for the case of tau leptons.

III. CP VIOLATION

CP violation in the decay $B \to X_s l^+ l^-$ is strongly suppressed in the SM following from the unitarity of the CKM matrix. However, in the semi-leptonic B decay, $B \to X_d l^+ l^-$, the CP violating effects can be quite sizeable. The CP asymmetry for this decay can be observed by measuring the partial decay rates for the process and its charge conjugated process [10, 11]. Before turning to a derivation of CP violating asymmetries for the case of polarised final state leptons it is helpful to recall the unpolarised case.

A. Unpolarized case

In this case as CP violating rate asymmetry is given by

$$A_{\mathrm{CP}} := \frac{\Gamma_0 - \bar{\Gamma}_0}{\Gamma_0 + \bar{\Gamma}_0} \ , \quad (14)$$

where

$$
\begin{aligned}
\Gamma_0 &\equiv \frac{d\Gamma}{d\hat{s}} \equiv \frac{d\Gamma(b \to dl^+l^-)}{d\hat{s}} \ , \\
\bar{\Gamma}_0 &\equiv \frac{d\bar{\Gamma}}{d\hat{s}} \equiv \frac{d\Gamma(\bar{b} \to \bar{d}l^+l^-)}{d\hat{s}} \ . \quad (15)
\end{aligned}
$$

The unpolarized particle decay rate Γ_0 can be found in Eq. (6). This can be rewritten as a product of a real-valued function $r(\hat{s})$ times the function $\Delta(\hat{s})$, given in Eq. (7); $\Gamma_0(\hat{s}) = r(\hat{s})\,\Delta(\hat{s})$. Following the prescription of [10] we may write the modulus of the matrix elements for the decay and the anti-particle decay as

$$|M| = |A + \lambda_u B| \ , \ |\bar{M}| = |A + \lambda_u^* B| \ , \quad (16)$$

where the CP-violating parameter λ_u, entering the Wilson coupling C_9^{eff}, has been defined in Eq. (3). Consequently, the rate for the anti-particle decay is then given by

$$\bar{\Gamma}_0 = \Gamma_{0|\lambda_u \to \lambda_u^*} = r(\hat{s})\bar{\Delta}(\hat{s}) \ ; \ \bar{\Delta} = \Delta_{|\lambda_u \to \lambda_u^*} \ . \quad (17)$$

The CP violating asymmetry following Eqs. (6) and (17) is obtained as

$$A_{\mathrm{CP}}(\hat{s}) = \frac{-2\mathrm{Im}(\lambda_u)\Sigma}{\Delta + 2\mathrm{Im}(\lambda_u)\Sigma} \simeq -2\mathrm{Im}(\lambda_u)\frac{\Sigma(\hat{s})}{\Delta(\hat{s})}, \quad (18)$$

in agreement with the result in [10]. In Eq. (18),

$$
\begin{aligned}
\Sigma(\hat{s}) &= \mathrm{Im}(\xi_1^*\xi_2)[F_3(\hat{s}) + 6\hat{m}_l^2 F_1(\hat{s})] \\
&\quad +6\mathrm{Im}(C_7^{\mathrm{eff}}\xi_2)F_1(\hat{s})(1 + \frac{2\hat{m}_l^2}{\hat{s}}) \ . \quad (19)
\end{aligned}
$$

If we choose the lepton l^- to be polarized, the above CP asymmetry gets modified and receives a contribution from C_{10} through the interference piece with C_9^{eff} in $|M|^2$; see Eqs. (11) and (13).

B. Polarized case

In this case, we define the CP violating asymmetry as

$$A_{\mathrm{CP}}(\mathbf{n}) := \frac{\Gamma(\mathbf{n}) - \bar{\Gamma}(\bar{\mathbf{n}} = -\mathbf{n})}{\Gamma_0 + \bar{\Gamma}_0} \ , \quad (20)$$

where

$$
\begin{aligned}
\Gamma(\mathbf{n}) &\equiv \frac{d\Gamma(\hat{s}, \mathbf{n})}{d\hat{s}} \equiv \frac{d\Gamma(b \to dl^+l^-(\mathbf{n}))}{d\hat{s}} \ , \\
\bar{\Gamma}(\bar{\mathbf{n}}) &\equiv \frac{d\bar{\Gamma}(\hat{s}, \bar{\mathbf{n}})}{d\hat{s}} \equiv \frac{d\Gamma(\bar{b} \to \bar{d}l^+(\bar{\mathbf{n}})l^-)}{d\hat{s}} \ , \quad (21)
\end{aligned}
$$

and Γ_0, $\bar{\Gamma}_0$ are functions as defined earlier. In addition, $\mathbf{n}$ is the spin direction of the lepton l^- in the b-decay and $\bar{\mathbf{n}}$ is the spin direction of the l^+ in the $\bar{b}$-decay. For instance, assuming CP conservation, the rate for the decay of a B to a left handed electron should be the same as the rate for the decay of a $\bar{B}$ to a right handed positron. Following

similar arguments as in the preceding section one obtains the following results for the CP violating asymmetries for a lepton l^- with polarisation $\mathbf{n} = \mathbf{e}_i$ (i = L, T, N) [9]:

$$A_{\rm CP}(\mathbf{n} = \pm\mathbf{e}_i) = \frac{1}{2}\left[A_{\rm CP}(\hat{s}) \pm \frac{\Delta P_i - (\Delta P_i)_{|\lambda_u \to \lambda_u^*}}{\Delta(\hat{s}) + \bar{\Delta}(\hat{s})}\right]$$

$$\equiv \frac{1}{2}\left[A_{\rm CP}(\hat{s}) \pm \delta A_{\rm CP}^i(\hat{s})\right]. \qquad (22)$$

One can see that the unpolarized CP violating asymmetry $A_{CP}(\hat{s})$ as obtained in Eq. (18) is altered by the polarised quantities $\delta A_{\rm CP}^i(\hat{s})$ which we obtain as

$$\delta A_{\rm CP}^i(\hat{s}) = \frac{-2{\rm Im}(\lambda_u)\delta\Sigma^i(\hat{s})}{\Delta(\hat{s}) + 2{\rm Im}(\lambda_u)\Sigma(\hat{s})} \simeq -2{\rm Im}(\lambda_u)\frac{\delta\Sigma^i(\hat{s})}{\Delta(\hat{s})}, \qquad (23)$$

with

$$\delta\Sigma^{\rm L}(\hat{s}) = {\rm Im}(C_{10}\xi_2)\,(1 + \hat{s} - 2\hat{s}^2)\,a\,,$$

$$\delta\Sigma^{\rm T}(\hat{s}) = \frac{3\pi\hat{m}_l}{2\sqrt{\hat{s}}}(1 - \hat{s})\left[-2{\rm Im}(C_7^{\rm eff}\xi_2)\right.$$
$$\left. +\frac{1}{2}{\rm Im}(C_{10}\xi_2) - \hat{s}{\rm Im}(\xi_1^*\xi_2)\right],$$

$$\delta\Sigma^{\rm N}(\hat{s}) = \frac{3\pi\hat{m}_l}{2\sqrt{\hat{s}}}(1 - \hat{s})\left[\frac{\hat{s}}{2}{\rm Re}(C_{10}\xi_2)\right]a\,, \qquad (24)$$

where a is the threshold factor defined below Eq. (9). Interestingly, we note that the asymmetries $\delta\Sigma^{\rm T}(\hat{s})$ and $\delta\Sigma^{\rm N}(\hat{s})$ have different combinations involving the imaginary and real parts of ξ_2. Note also that for a given polarisation there are two independent observables, $A_{\rm CP}(\mathbf{n} = \mathbf{e}_i)$ and $A_{\rm CP}(\mathbf{n} = -\mathbf{e}_i)$ or, alternatively, $A_{CP}(\hat{s}) = A_{\rm CP}(\mathbf{n} = \mathbf{e}_i) + A_{\rm CP}(\mathbf{n} = -\mathbf{e}_i)$ and $\delta A_{\rm CP}^i(\hat{s}) = A_{\rm CP}(\mathbf{n} = \mathbf{e}_i) - A_{\rm CP}(\mathbf{n} = -\mathbf{e}_i)$.

IV. NUMERICAL ANALYSIS AND DISCUSSION

With the above basic analytic framework, we are ready to discuss our numerical results. The basic and essential information is summarised in figures 1 to 4.

The currently allowed range for the Wolfenstein parameters is given by $0.190 < \rho < 0.268$, $0.284 < \eta < 0.366$. For our analysis we take $(\rho, \eta) = (0.25, 0.34)$. In terms of the Wolfenstein parameters, ρ and η, the parameter λ_u is given by the relation,

$$\lambda_u = \frac{\rho(1 - \rho) - \eta^2}{(1 - \rho)^2 + \eta^2} - i\frac{\eta}{(1 - \rho)^2 + \eta^2} + \cdots \quad. \qquad (25)$$

The results for other values of these parameters can be easily obtained: Noticing that since $C_9^{\rm eff}(\hat{s})$ only very weakly depends on ρ and η, almost the entire dependence is due the prefactors containing the CKM matrix elements; particularly, in the expressions for the branching ratio and the CP violating asymmetries. In the case of the branching ratio this is the term $|V_{tb}V_{td}^*/V_{cb}|^2 =$
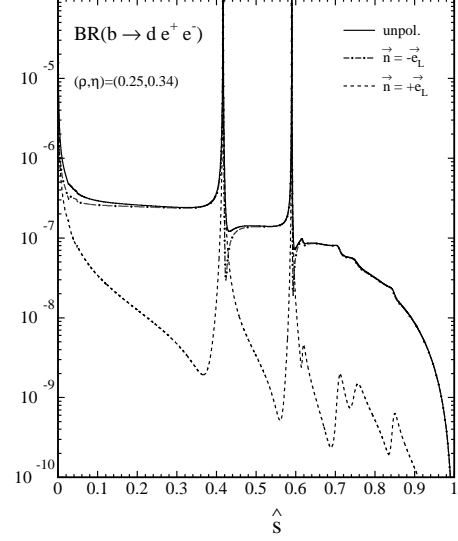

FIG. 1: Polarised and unpolarised branching ratios for the decay $b \to de^+e^-$ according to Eq. (9) and (11). The unit vector $\mathbf{e}_{\rm L}$ has been defined in Eq. (10).
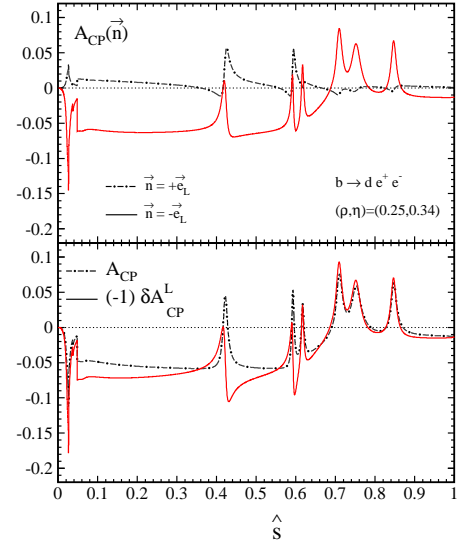

FIG. 2: Polarised and unpolarised CP violating rate asymmetries for the decay $b \to de^+e^-$ as given in Eqs. (22), (23) and (18), respectively.

$\lambda^2[(1 - \rho)^2 + \eta^2]$; in the case of the CP violating asymmetries it is the factor ${\rm Im}\lambda_u = -\eta/((1 - \rho)^2 + \eta^2)$. The results for other Wolfenstein parameters can therefore be obtained by simply rescaling the shown results. For instance varying (ρ, η) in the allowed range leads to a variation of $|{\rm Im}\lambda_u|$ in the range $(0.54 \div 0.38)$. (For $(\rho, \eta) = (0.25, 0.34)$ we find $|{\rm Im}\lambda_u| = 0.5$.) As can be
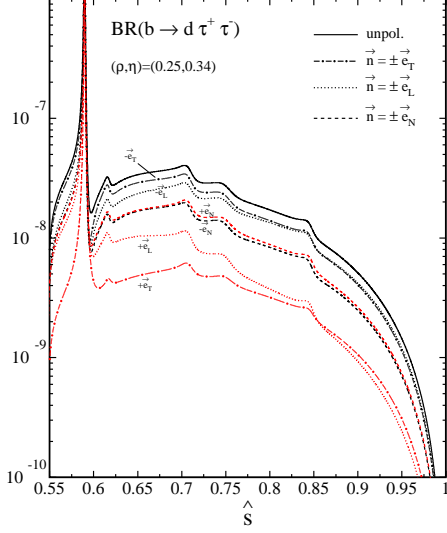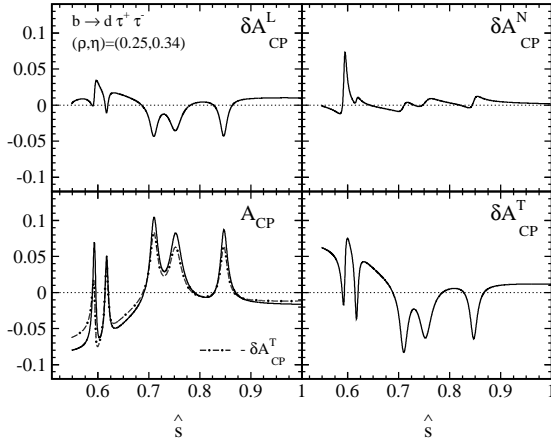
FIG. 3: As in Fig. 1 for the decay $b \to d\tau^+\tau^-$.

FIG. 4: Polarised and unpolarised CP violating rate asymmetries for the decay $b \to d\tau^+\tau^-$ as given in Eq. (23) and (18), respectively.

seen the absolute value of the CP violating asymmetries increases with increasing ρ and η. On the other hand, the branching ratios mildly decrease with increasing ρ.

In Fig. 1, we display the branching ratios for the decay $b \to de^+e^-$ with unpolarized and longitudinally polarized electrons. The unpolarized branching ratio (solid line) has been obtained with help of Eq. (9). The corresponding results for polarised final state leptons have been calculated accordingly using Eq. (11). The dash-dotted and dotted lines corresponds to $\mathbf{n} = -\mathbf{e}_L$ and $\mathbf{n} = +\mathbf{e}_L$, respectively, where the unit vector $\mathbf{e}_L$ has been defined in Eq. (10). As can be seen, in the SM, the decay

is naturally left-handed and hence the polarised spectrum for $\mathbf{n} = -\mathbf{e}_L$ is very similar to the unpolarised spectrum. In the kinematical region between the $\rho - \omega$ and $c\bar{c}$ resonances, which is theoretically the cleanest kinematic bin, the branching ratio is $\sim 3 \times 10^{-7}$. On the other hand, the polarised $\mathbf{n} = \mathbf{e}_L$ spectrum is far below the unpolarised one. This feature can provide for measurements involving a new physics search. In the following we will classify such polarized decays whose SM decay width is much smaller than the unpolarized spectrum as *wrong sign* decay.

In Fig. 2, we present results for the polarised and unpolarised CP violating rate asymmetries calculated according to Eqs. (22), (23), and (24) for the decay $b \to de^+e^-$. We find that the asymmetries for $b \to d\mu^+\mu^-$ are numerically similar to the results shown here, and hence are not presented. As mentioned earlier, only two of the shown four quantities are linearly independent. As can be observed, $A_{\mathrm{CP}}(\mathbf{n} = -\mathbf{e}_L)$ is much larger than the asymmetry with opposite lepton polarization implying that $A_{\mathrm{CP}}(\mathbf{n} = -\mathbf{e}_L)$ is quite similar to the unpolarized asymmetry A_{CP}. This can be also seen by the lower half of Fig. 2 where the unpolarized A_{CP} and $(-1)\delta A_{\mathrm{CP}}^{\mathrm{L}}$ have been plotted. Here, $A_{\mathrm{CP}}(\mathbf{n} = -\mathbf{e}_L)$ would be the average of the two curves (lying in the middle between them). Note that the polarised CP violating asymmetry $\delta A_{\mathrm{CP}}^{\mathrm{L}}$ is comparable and in certain kinematic regions even larger than its unpolarized counterpart. Particularly, in the theoretically clean region, between the $\rho-\omega$ and the $c\bar{c}$ resonances, we find $\delta A_{\mathrm{CP}}^{\mathrm{L}}$ is about 8% when compared to about 5% in the unpolarized case [10, 11]. However, in the resonance regions, the polarised asymmetry can reach values as large as up to 20% (ρ–ω) and 11% ($c\bar{c}$), respectively.

The polarised asymmetries $\delta A_{\mathrm{CP}}^{\mathrm{N}}$ and $\delta A_{\mathrm{CP}}^{\mathrm{T}}$ are proportional to the lepton mass and therefore only relevant in the case of final state tau leptons. In Fig. 3, branching ratios for the decay $b \to d\tau^+\tau^-$ are shown for unpolarized (solid line), longitudinally (dotted), normally (dashed), and transversely (dash-dotted) polarized taus. The corresponding branching ratio is $\sim \mathcal{O}(1 \times 10^{-8})$, requiring a larger luminosity. One can see that for $\mathbf{n} = \pm\mathbf{e}_N$ both rates are very similar, whereas, for $\mathbf{n} = \pm\mathbf{e}_T$, the $-\mathbf{e}_T$ state is strongly favored, as being closer to the unpolarised decay width. Therefore, we would classify the polarised $\mathbf{n} = \mathbf{e}_T$ spectra as a *wrong sign* decay.

In Fig. 4, we show both the polarised and unpolarised CP violating rate asymmetries calculated according to Eqs. (22), (23), and (24) for the decay $b \to d\tau^+\tau^-$. Since $\delta A_{\mathrm{CP}}^{\mathrm{L}}$ and $\delta A_{\mathrm{CP}}^{\mathrm{N}}$ are small we conclude that $A_{\mathrm{CP}}(\mathbf{n} = +\mathbf{e}_L) \simeq A_{\mathrm{CP}}(\mathbf{n} = -\mathbf{e}_L)$ and $A_{\mathrm{CP}}(\mathbf{n} = +\mathbf{e}_N) \simeq A_{\mathrm{CP}}(\mathbf{n} = -\mathbf{e}_N)$. On the other hand, $\delta A_{\mathrm{CP}}^{\mathrm{T}}$ is comparable to the unpolarized A_{CP} as is indicated by the dash-dotted line in the $(2,1)$-panel. This in turn implies that $A_{\mathrm{CP}}(\mathbf{n} = +\mathbf{e}_T)$ is very small. As can be observed, all calculated asymmetries, reach at the maximum about 10%.

V. SUMMARY

To conclude, we have performed a detailed study of the CP asymmetry for the process $b \rightarrow dl^+l^-$ updating the unpolarised case and including the case when one of the leptons is in a polarised state. Our results indicate that when a lepton is in a certain polarised state $(-\mathbf{e}_L, -\mathbf{e}_T)$, the decay rates are comparable to the unpolarised spectrum. For normally polarised leptons, both polarisations $\pm\mathbf{e}_N$ give similar widths but lower than in the case of $-\mathbf{e}_L$ and $-\mathbf{e}_T$. The remaining polarisation states, which we had defined to be the *wrong sign* states, the decay rates and the corresponding asymmetries are lower, when compared to the unpolarised SM results. For the kinematic regions which are away from resonance, the polarised CP asymmetries are larger than the unpolarised asymmetry. Furthermore, the resonance regions show a large asymmetry and in all of our analysis, we have included the $\rho - \omega$ resonance states also. However, unfortunately, these results in the resonance region suffer from theoretical uncertainties.

An observation of a 3σ signal for $A_{CP}(\hat{s})$ requires about $\sim 10^{10}$ B mesons [10]. For such a measurement a good d-quark tagging is necessary to distinguish it from the much more copious decay $b \rightarrow sl^+l^-$ and hence will be a challenging task at future hadronic collider experiments like LHCb, BTeV, ATLAS or CMS [21]. More dedicated experiments like Super-BABAR and Super-BELLE should be able to achieve this goal. BELLE and BABAR have already measured the rare decay $b \rightarrow sl^+l^-$ which could be measured with great accuracy at these high luminosity upgrades. Given enough statistics, and excellent kaon/pion identification, they may be able to measure $b \rightarrow dl^+l^-$ or the exclusive process $B \rightarrow \rho l^+l^-$.

In the polarized case, for measuring $A_{CP}(\mathbf{n} = -\mathbf{e}_L)$ we need a similar number of produced B-mesons, provided an efficient polarisation measurement is possible, since the branching rates are very much alike as discussed previously.

The polarisation observables are also interesting with respect to new physics searches since they involve different quadratic combinations of the Wilson couplings as compared to unpolarised observables. In this respect, given a real valued C_{10} (for the SM), we note that the asymmetries $\delta\Sigma^T$ and $\delta\Sigma^N$ can be of relevance through the contributions arising from the real and imaginary parts of the function ξ_2 as can be inferred from Eq. (24). In addition, due to the left-handed nature of the SM interactions the electrons and muons are predominantly in the $-\mathbf{e}_L$ state. Hence measuring a muon in a *wrong sign* polarised state $(+\mathbf{e}_L)$ can be very sensitive to new physics. Essentially, we need to probe polarised $(+\mathbf{e}_L)$ muons which we expect to be possible by (i) angular distribution of the decay products and (ii) through the life time of the $+\mathbf{e}_L$ muons, which is enhanced as compared to the $-\mathbf{e}_L$ state due to the dynamics of the SM interaction (left-handed). This is also evident by their smaller decay width as observed in Fig. 1. The situation for the case of the tau leptons is different and we observe that the $\mathbf{e}_T$ polarised state can be most sensitive to new physics as can be seen in Fig. 3.

Acknowledgments

[1] For a recent review, see A. J. Buras, hep-ph/0101336.
[2] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. **D2**, 1285 (1970).
[3] M. Battaglia *et al.*, *The CKM matrix and the unitarity triangle*, hep-ph/0304132.
[4] P. Gambino and M. Misiak, Nucl. Phys. **B611**, 338 (2001), hep-ph/0104034.
[5] A. J. Buras, A. Czarnecki, M. Misiak, and J. Urban, Nucl. Phys. **B631**, 219 (2002), hep-ph/0203135.
[6] S. Glenn *et al.* (CLEO), Phys. Rev. Lett. **80**, 2289 (1998), hep-ex/9710003.
[7] A. Ali, G. Hiller, L. T. Handoko, and T. Morozumi, Phys. Rev. **D55**, 4105 (1997), hep-ph/9609449.
[8] J. Kaneko *et al.* (Belle), hep-ex/0208029.
[9] K. S. Babu, K. R. S. Balaji, and I. Schienbein, Phys. Rev. **D68**, 014021 (2003), hep-ph/0304077.
[10] F. Krüger and L. M. Sehgal, Phys. Rev. **D55**, 2799 (1997), hep-ph/9608361.
[11] A. Ali and G. Hiller, Eur. Phys. J. **C8**, 619 (1999), hep-ph/9812267.
[12] T. M. Aliev, V. Bashiry, and M. Savci, hep-ph/0308069.

[13] A. J. Buras and M. Münz, Phys. Rev. **D52**, 186 (1995), hep-ph/9501281.
[14] G. Buchalla, A. J. Buras, and M. E. Lautenbacher, Rev. Mod. Phys. **68**, 1125 (1996), hep-ph/9512380.
[15] M. Misiak, Nucl. Phys. **B439**, 461(E) (1995).
[16] M. Jezabek and J. H. Kühn, Nucl. Phys. **B320**, 20 (1989).
[17] A. F. Falk, M. E. Luke, and M. J. Savage, Phys. Rev. **D49**, 3367 (1994), hep-ph/9308288.
[18] J. L. Hewett, Phys. Rev. **D53**, 4964 (1996), hep-ph/9506289.
[19] F. Krüger and L. M. Sehgal, Phys. Lett. **B380**, 199 (1996), hep-ph/9603237.
[20] See for example, D. Guetta and E. Nardi, Phys. Rev. **D58**, 012001 (1998).
[21] N. Harnew, *The B physics potential of LHCb, BTeV, ATLAS and CMS*, Prepared for 8th International Symposium on Heavy Flavor Physics (Heavy Flavors 8), Southampton, England, 25-29 Jul 1999.